ERDC/TN APCRP-EA-06
September 2003

Manipulation of Sediment Nitrogen via Dewatering and Rehydration: Implications for Macrophyte Control and Nitrogen Dissipation

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PURPOSE: This technical note examines macrophyte growth response to changes in sediment nitrogen (N) concentrations due to sediment dewatering and rehydration. Results of this study may be used to better understand sediment N changes as a result of a lake drawdown and have implications for control of macrophyte growth.

BACKGROUND: Information is needed regarding the impacts of sediment dewatering and rehydration on sediment N dynamics and N availability for macrophyte growth. Research has demonstrated that sediment desiccation, followed by rehydration, can result in the mineralization of organic N to ammonia (De Groot and Van Wijck 1993), which can serve as a source of inorganic N for macrophyte growth. However, little is known about N dynamics during partial sediment dewatering and rehydration. Since sediment N usually regulates the growth of rooted macrophytes (Barko and James 1998), manipulations of aquatic sediment via temporary pool drawdown and dewatering may be desirable to improve (or diminish) sediment N conditions and availability for macrophyte growth in shallow lakes. Pool 8, a run-of-the-river impoundment of the Upper Mississippi River system, underwent water level drawdown during the summer (2001) to dewater and consolidate sediments for stimulation of submersed and emergent macrophyte growth (Scheffer 1998). Our objectives were to expand information obtained earlier on sediment nutrient dynamics due to dewatering (James et al. 2002) by quantifying changes in sediment N characteristics and macrophyte growth response on sediments collected from a shallow backwater region of this pool (Lawrence Lake) that were experimentally dewatered to lower moisture contents and then rehydrated.

METHODS: Lawrence Lake is a shallow (mean depth = 0.5 m) backwater region located on the Minnesota side of Pool 8, Upper Mississippi River (Figure 1). Submersed and emergent macrophytes occur in the lake. In October 2000, over 50 intact replicate sediment cores were collected at a station (depth = 0.75 m) located near the entrance of the lake using a Wildco KB sediment core sampler (Wildlife Supply Co., Saginaw, MI) equipped with a plastic core liner (7.6 cm diam and 20 cm long). In the laboratory, the upper 8 cm of sediment were carefully extruded into a core liner that was precut to exactly 10 cm. A rubber stopper was used to seal the bottom of each extruded sediment core. The sediment systems were dewatered in the laboratory under controlled temperature conditions (~20 °C) in a darkened room with ambient air circulation. During the initial stages of the dewatering process, only the upper surface of the sediment core was directly exposed to air. Dewatering and consolidation of the core over time resulted in exposure of its sides and upper surface to air. Sediment cores were dewatered from an initial moisture content of 75 percent (treatment 1 = 0 percent dewatered) to 61 percent (treatment 2 = ~20 percent dewatered), 32 percent (treatment 3 = ~60 percent dewatered), and 5 percent (treatment 4 = ~95 percent dewatered) moisture content.

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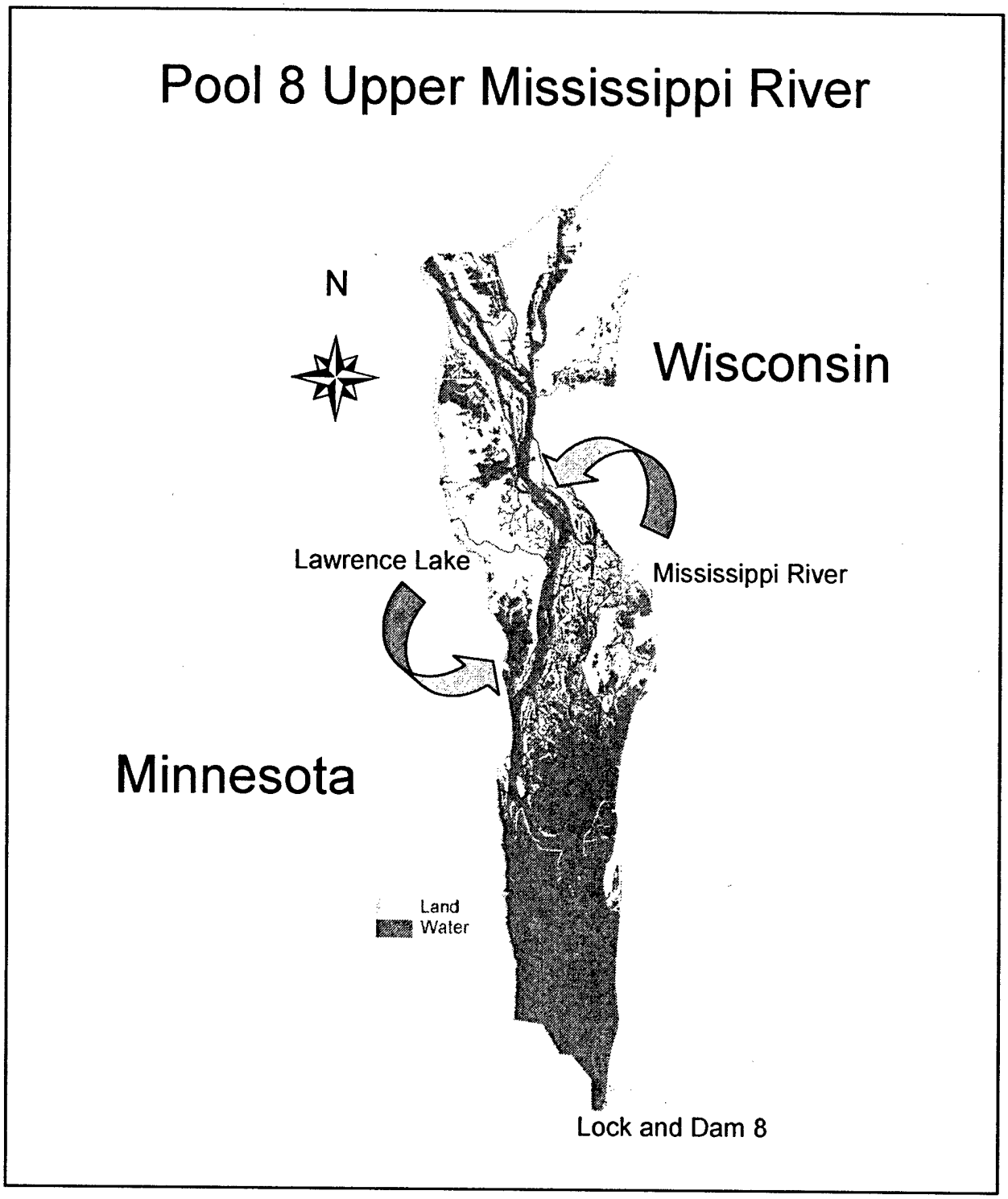

Figure 1. Pool 8 of the Upper Mississippi River system and the location of the shallow backwater Lawrence Lake

In order to estimate the loss of moisture from sediment cores over time, the 10-cm core liner and rubber stopper were weighed before and immediately after extrusion of sediment into them. The loss of sediment moisture during dewatering was calculated by difference and converted to a percentage of the initial moisture content. For treatments 2 through 4, four replicate sediment systems in the dewatered state were sacrificed for analytical determinations. Four additional replicate cores were rehydrated for a period of 2 weeks before analysis. These sediments were rehydrated with 100 mL of lake water (collected from Lawrence Lake) that had been previously filtered through a glass fiber filter (Gelman A/E). The sediment cores were completely covered with water so that direct rehydration could occur via exposure of the top and sides of the sediment core. The systems were covered with plastic film to minimize evaporative losses during the 2-week period. The volume of water remaining (i.e., not soaked up by the sediment) prior to sediment analysis was measured and analyzed for total nitrogen (N), ammonium-N (NH_4-N), and nitrate+nitrite-N (NO_3+NO_2-N) using standard analytical techniques (APHA 1992; see below). Three sediment systems that had been sealed to prevent dewatering served as controls and were also sacrificed for analysis.

For each treatment, sediment core dimensions (height and diameter) were measured and the sediment was gently homogenized prior to analysis. Fresh sediment was carefully placed in a crucible of known volume and dried at 105 °C to a constant weight to determine moisture content and sediment density (Allen et al. 1974). For treatment 4 (95 percent dewatered), density was determined by measuring the displacement of distilled water in a volumetric cylinder by a sub-sample of the sediment. Total sediment N was analyzed colorimetrically using Lachat QuikChem procedures following digestion with sulfuric acid, potassium sulfate, and red mercuric oxide (Plumb 1981). Exchangeable sediment N (as ammonium) was determined by cation exchange with 1 m sodium chloride according to Bremner (1965).

Rates of N release from sediments under oxic and anoxic conditions were determined using additional sediment cores that were subjected to treatments 1 through 4 and then rehydrated for 2 weeks. Experimental cores were transferred to a core liner (6.5-cm ID and 25-cm length) and 300 mL of filtered (Gelman A/E glass fiber) lake water were siphoned onto the sediment. The systems were sealed with rubber stoppers. For treatments 3 and 4, consolidation of sediments resulted in a decrease in the sediment surface area and core length. Thus, surface area was much smaller than the diameter of the sediment incubation system for these treatments. The goal was to assess N diffusion between the upper surface of the sediment and overlying water for all treatments. Thus, to prevent exposure of the side surfaces of the core to overlying water during N release analysis, the sides of the core were first gently wrapped in two layers of cellophane (leaving the upper surface exposed), then fine-grain sand was gently packed around the sides of the core after placement in the incubation system. The redox environment in each system was controlled by bubbling the water with air (for oxic conditions) or nitrogen (for anoxic conditions). Sediment systems were incubated at 20 °C over a 1-week period to simulate in situ temperatures during summer. Samples were collected in the middle of the water column in each system on a daily basis for NH_4-N and NO_3+NO_2-N analysis. Rates of N release from the sediment (mg m^{-2} d^{-1}) were calculated as the linear change in concentration in the overlying water divided by time and the upper surface area of the sediment. Changes in the surface area of the sediment core due to dewatering were, therefore, factored into the rate calculations.

Sediments collected in October 2000 from the same location in Lawrence Lake were used to examine macrophyte growth response as a function of sediment dewatering and rehydration. Prior to the initiation of growth experiments, a preliminary study was conducted to determine the rate of dewatering in order to predict the length of time required to dewater sediments to specific moisture contents. For the experiment, approximately 3 kg of completely homogenized (gently stirred) sediments were placed in 4-L containers (16 cm wide, 16 cm deep, 22 cm high); the initial depth of the sediment in the containers was 10 cm. The containers were sealed and refrigerated at 4 °C until the start of the dewatering process (approximately 2 months). Using the dewatering rate information collected in the preliminary study, containers were pulled from refrigeration at various time intervals, opened, and allowed to dry to the target moisture content (i.e., 20, 60, and 95 percent dewatered) at room temperature (~ 20 °C) in a darkened area. The objective was to have all sediment systems reach their target moisture contents simultaneously by early June 2001. Loss of moisture from the sediments was monitored via changes in mass (see above) of the sediment containers to determine when target moisture contents were reached. When the target was reached, the sediment containers were resealed to prevent further moisture loss until the start of the experiment. All systems were rehydrated with 1 L from a local tap water source (Ca = 57 mg L^{-1}; Conductivity = 422 µS; Mg = 28 mg L^{-1}; NO_3+NO_2-N = 0.2 mg L^{-1}; K = 0.8 mg L^{-1}; Na = 1.6 mg L^{-1}; SO_4 = 21 mg L^{-1}; pH = 7.8) for a period of 4 days prior to planting. Fine-grain sand was poured along the sides of compacted (i.e., treatments 3 and 4), rehydrated sediment to account for lost sediment volume prior to planting.

Potamogeton pectinatus was used as the experimental macrophyte in the growth response studies. Propagules obtained commercially (Kester's W.F.G. Nurseries, Omro, WI), were germinated prior to initiation of the experiment. One sprout was transplanted in each experimental sediment container shortly after target moisture contents were reached and sediments were rehydrated. Six replicates were planted for each treatment for a total of 24 containers. Additional replicate sediment containers, subjected to the same desiccation-rehydration scenarios (six replicates per treatment), were not planted with macrophytes and served as controls to monitor initial sediment conditions (i.e., before and after dewatering and rehydration).

The control and planted containers were incubated in clear plastic tanks (1.2 m diam × 1.2 m height) that were placed in a large outdoor facility consisting of four swimming pools (4.6 m diam × 1.2 m deep). Four tanks were placed in each pool for a total of 16 tanks. The pools served as water baths to moderate temperatures in the summer. The temperature in each pool was controlled to a certain extent with water temperature controllers (Remcor CFF500). Water clarity in the pools was maintained using sand filters. Only three planted containers were placed at the bottom of each tank (1 m from the water surface) to minimize crowding and shading during the growing period. The containers were placed randomly in tanks in the outdoor facility. All tanks and pools were filled with tap water prior to the start of the experiment.

During the growing period, the tanks were protected with clear acrylic covers that allowed airflow from the sides but prevented rain and debris from falling into the tanks. Airlift pumps were placed in each tank to promote circulation. At weekly intervals, half of the water in each tank was carefully flushed with replacement fresh tap water amended with KCl to attain a concentration of 6 mg L^{-1} (Smart and Barko 1985). Each tank was also filtered 1-2 times a week (diatomaceous earth filters) to minimize and remove algal growth. Water temperature of the four pools and PAR

(photosynthetically active radiation) striking the water surface (Licor cosine quantum radiometer) were monitored continuously during the experiment. Underwater PAR (Licor Model LI1000) at the bottom of each pool (1.0 m) was determined daily near solar noon. The experiment was initiated on 18 June and ended on 31 July 2001. At the end of the experiment, shoots were harvested from each container for determination of biomass and N content. Biomass was measured to the nearest 0.1 g after drying at 40 °C. Macrophyte N content was determined according to Allen et al. (1974).

RESULTS AND DISCUSSION

Experimental sediment dewatering and rehydration. During the dewatering process, sediment cores lost water at a rate of 1.5 percent water mass d^{-1}. Near complete dryness occurred in approximately 60 days. Sediment cores consolidated as a consequence of water loss, resulting in a decline in sediment core length from an initial mean of 8.5 cm to a final mean of 4.6 cm after nearly complete desiccation. Core diameter declined from an initial mean of 6.6 cm to a final mean of 4.5 cm after nearly complete desiccation.

Mean moisture content and sediment density exhibited a hysteretic pattern as a result of dewatering and rehydration (Figure 2). Rehydration of sediments that were dewatered by 20, 60, and 95 percent resulted in an overall lower mean moisture content, and higher mean density, compared to initial mean sediment conditions (i.e., day 0 and no dewatering). As the percentage of water removed from sediment increased, there was a trend of greater rebound in mean moisture content and mean density conditions upon rehydration. Thus, drier sediments gained more water than wetter sediments during the rehydration process. However, the mean moisture content of rehydrated sediment was lower, while mean sediment density was higher, as a function of increased dewatering. In contrast, mean moisture content and sediment density in the control treatments, which were not dewatered, remained similar to initial mean sediment conditions over time.

The mean concentration of exchangeable sediment N declined significantly ($p < 0.05$) compared to initial concentrations as a function of the percentage of water removed (Figure 3). For sediments that were dewatered by 20 and 60 percent, rehydration did not result in any additional changes in mean concentration, as exchangeable sediment N remained low relative to initial conditions for these treatments. However, sediments dewatered by 95 percent exhibited substantial increases in mean exchangeable N after rehydration. In contrast, concentrations of exchangeable sediment N in control sediments fluctuated over time around a grand mean of 0.09 mg L^{-1} and exhibited no clear trend over time. Total sediment N remained constant over time for control sediments, but exhibited a trend of significantly lower concentrations compared to initial conditions for sediment dewatered by 95 percent and for sediment dewatered by 95 percent and then rehydrated (Figure 3). Overall, 95 percent dewatering of sediment resulted in a net loss of nearly 18 percent of the total sediment N and a 210-percent net gain of exchangeable sediment N. Final concentrations of total N and NH_4-N in the water used to rehydrate these sediments were high (30.3 mg L^{-1} for ammonium-N and 34.7 mg L^{-1} for total N), but did not account for overall losses in total sediment N.

Similar to patterns observed for mean exchangeable sediment N, mean rates of NH_4-N release from sediments declined substantially under both oxic and anoxic conditions as a result of dewatering

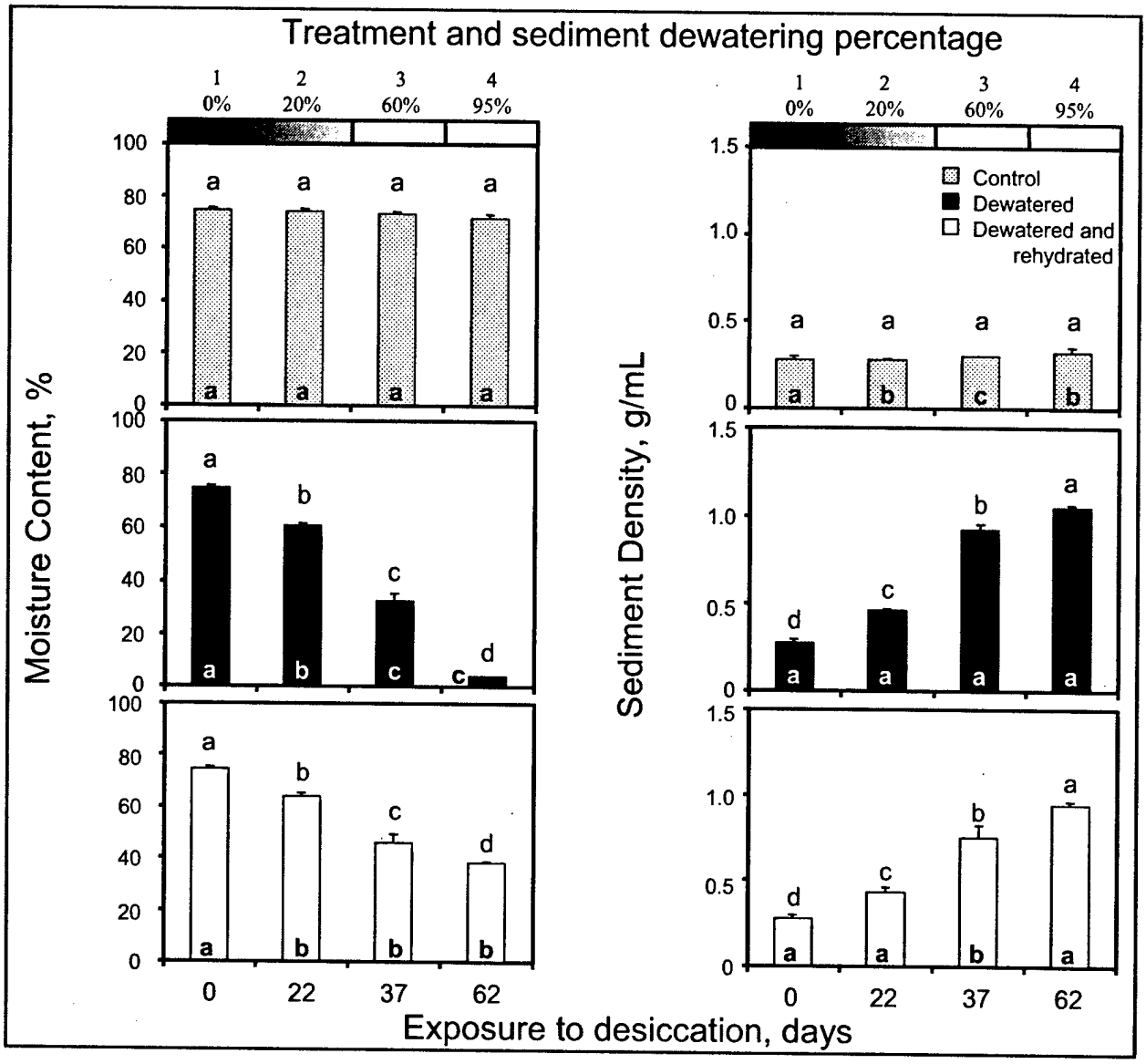

Figure 2. Variations in mean (1 S.E = vertical line above bar; n = 3-4) moisture content and sediment density as a function of exposure to desiccation. Control systems were not exposed to desiccation. Different letters above the bars represent significant differences ($p < 0.05$; Duncan-Waller ANOVA; SAS 1994) as a function of time exposure to desiccation while those letters located inside the bars represent significant differences as a function of the treatment (control, dewatered, or dewatered and rehydrated) of the sediment

sediment by 20 and 60 percent (Figure 4). In particular, mean rates of NH_4-N release were undetectable under oxic conditions for sediments dewatered by 60 percent. Dewatering the sediment by 95 percent, followed by rehydration, resulted in a marked increase in the mean rate of NH4-N release from sediments compared to initial rates. Mean rates of NO_3+NO_2-N release from sediments under oxic conditions exhibited similar patterns of declining values as sediments were partially dewatered and then rehydrated at a very high rate due to nearly complete desiccation and rehydration.

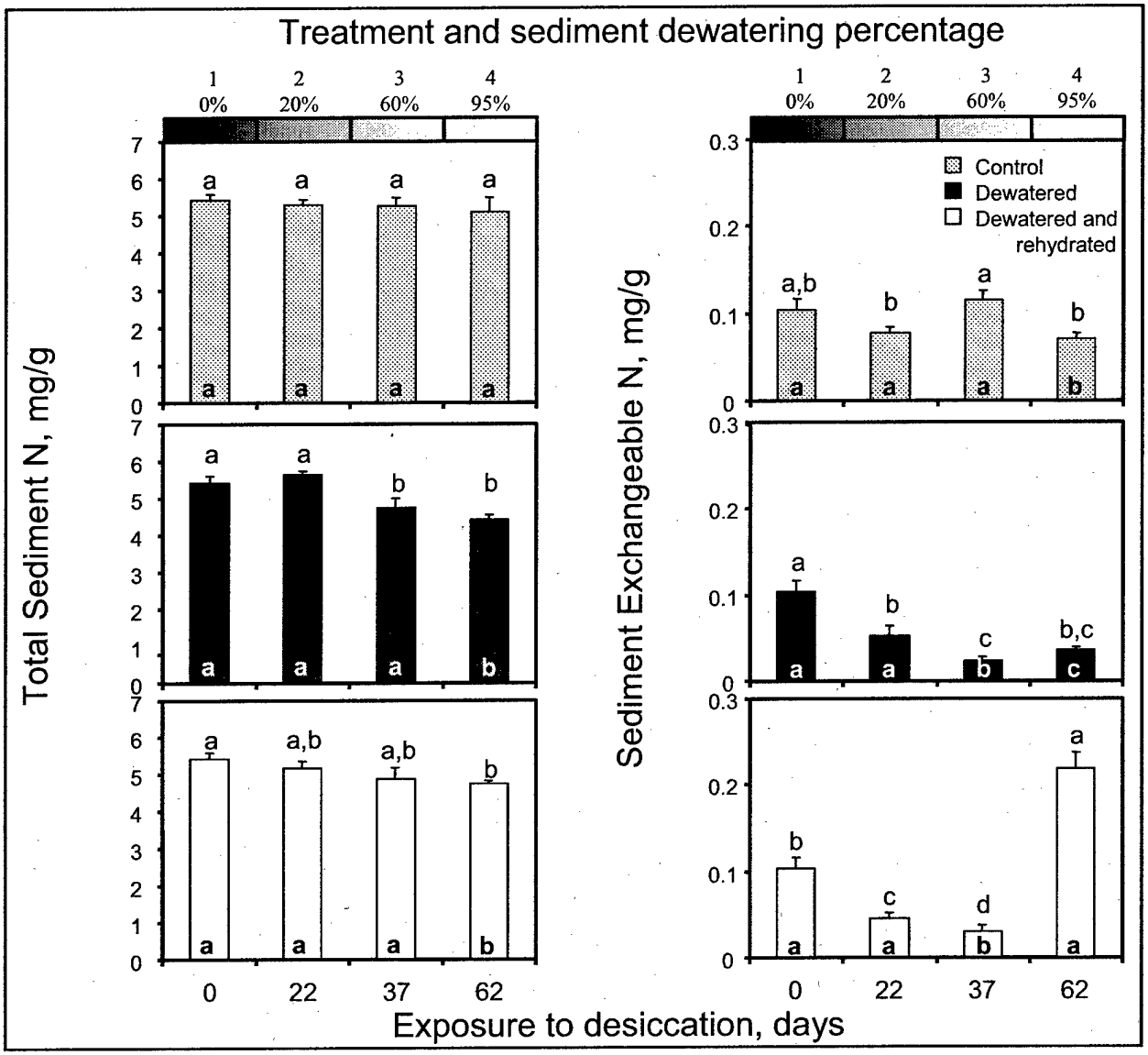

Figure 3. Variations in mean (1 S.E = vertical line above bar; n = 3-4) total and exchangeable sediment nitrogen (N) as a function of exposure to desiccation. Control systems were not exposed to desiccation. Letters above the bars represent significant differences ($p < 0.05$; Duncan-Waller ANOVA; SAS 1994) as a function of time exposure to desiccation while those letters located inside the bars represent significant differences as a function of the treatment (control, dewatered, or dewatered and rehydrated) of the sediment

Macrophyte growth response. Growth of *P. pectinatus* on sediments dewatered to various levels is shown in Figure 5. Plants grown on sediments that were dewatered by 20 and 60 percent exhibited a trend of lower mean biomass and tissue nitrogen mass, versus growth on control sediment that was not dewatered. Mean biomass and tissue nitrogen mass were significantly elevated for plants grown on sediment that was dewatered by 95 percent, compared to partially dewatered sediments (i.e., 20 and 60 percent). Mean tissue N mass was also significantly higher ($P < 0.05$; Statistical Analysis System (SAS) 1994) for plants grown on sediment that was dewatered by 95 percent versus controls.

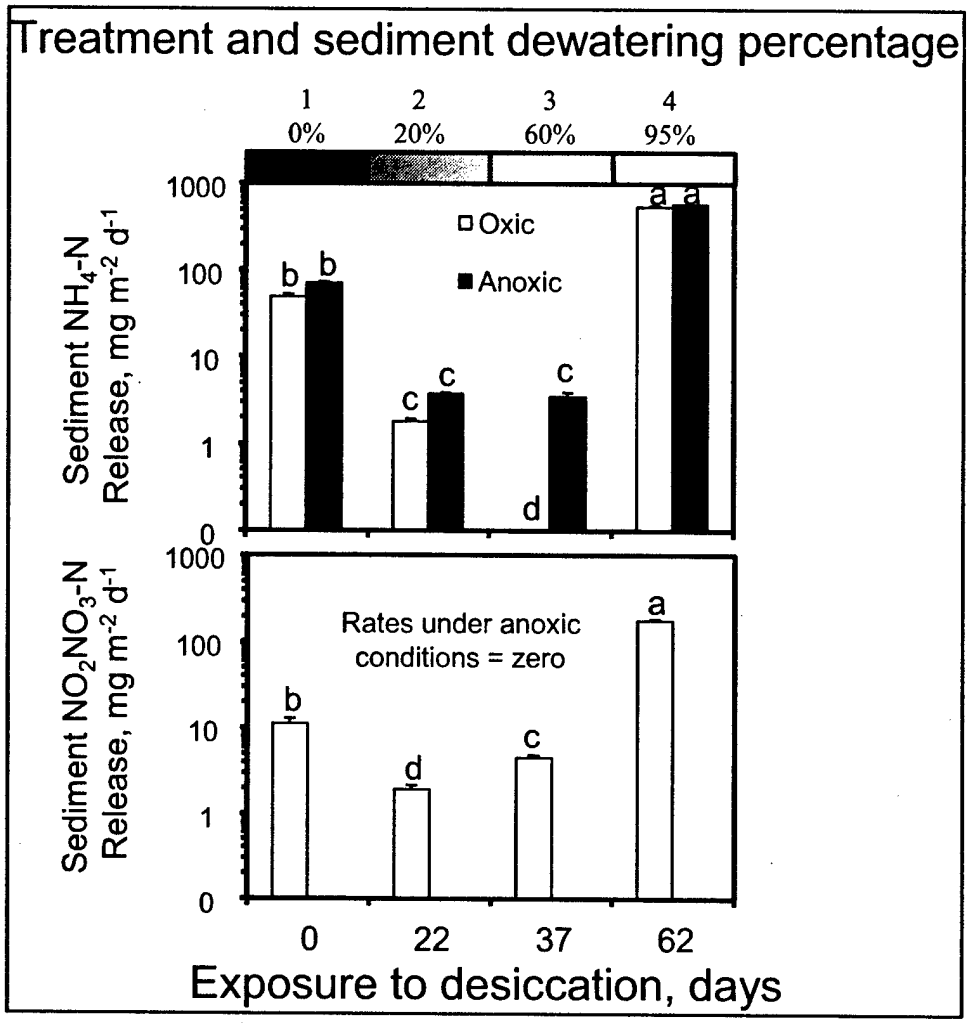

Figure 4. Variations in mean (1 S.E = vertical line above bar; n=3-4) rates of ammonium (NH_4-N) and nitrate-nitrite (NO_3+NO_2-N) release from sediments under oxic and anoxic conditions. Different letters above the bars represent significant differences ($p < 0.05$; Duncan-Waller ANOVA; SAS 1994) as a function of time exposure to desiccation

However, there were no statistical differences in mean biomass between these two treatments. Multiple regression analysis (SAS 1994) indicated that most of the variation in plant growth was attributed to variations in exchangeable sediment N ($r^2 = 0.64$ and 0.57 for biomass and tissue N mass, respectively) versus sediment moisture content and density.

Implications for manipulating sediments in shallow aquatic systems. Exchangeable sediment N levels of Lawrence Lake sediments could be manipulated to a certain extent via dewatering to regulate the growth of an experimental plant *P. pectinatus*. Partial desiccation of sediments followed by rehydration resulted in a decrease in the mean exchangeable sediment N concentration and a corresponding depression in the growth of *P. pectinatus*, relative to controls. Conversely, nearly complete desiccation of sediment followed by rehydration resulted in a substantial increase in exchangeable sediment N concentration and an increase in the growth of *P. pectinatus* relative to biomass levels for those plants grown on partially desiccated sediment.

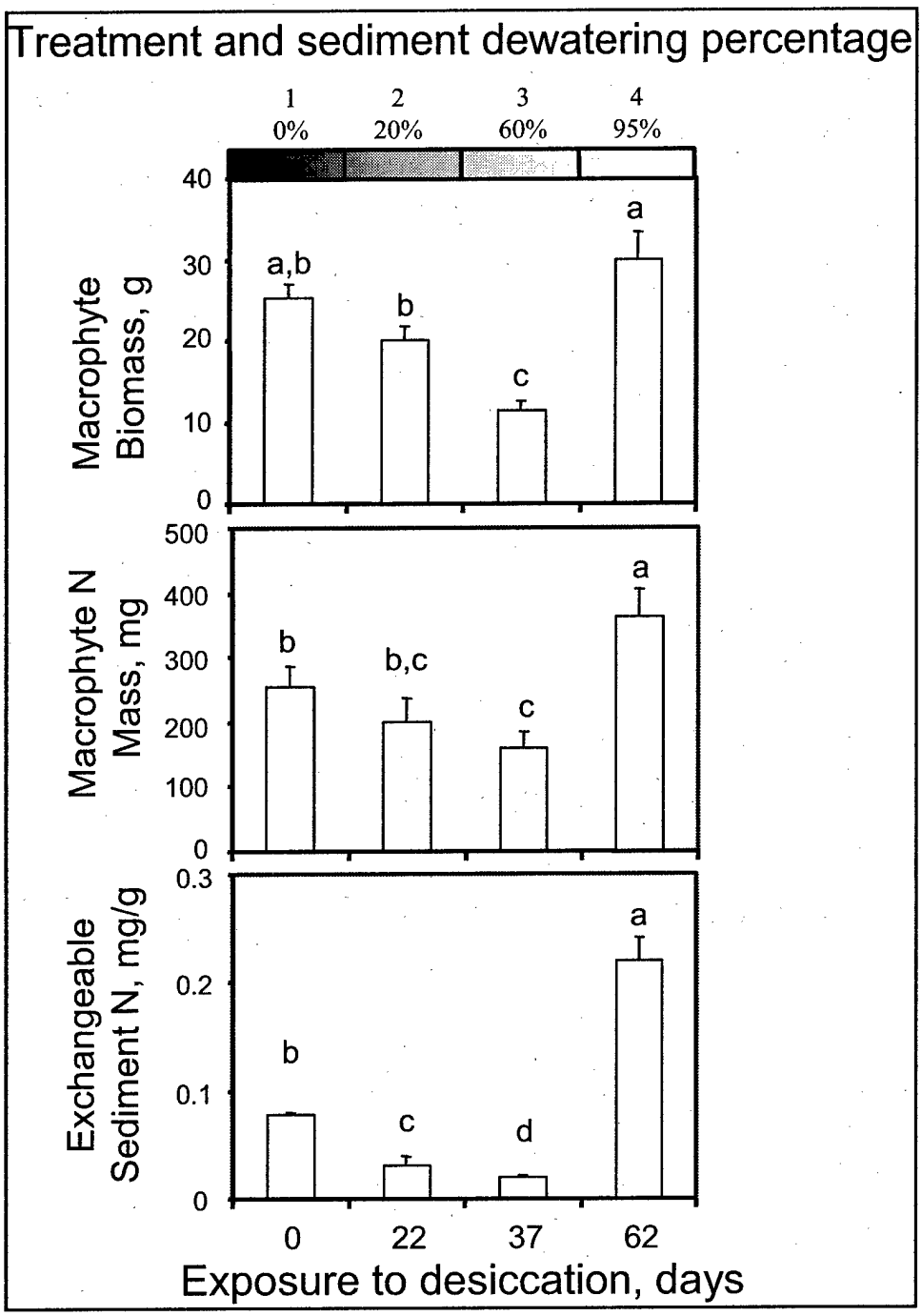

Figure 5. Variations in mean (1 S.E = vertical line above bar; n = 6) macrophyte biomass, macrophyte N mass, and exchangeable sediment N as a function of time exposure to desiccation. Different letters above the bars represent significant differences ($p < 0.05$; Duncan-Waller ANOVA; SAS 1994) as a function of exposure to desiccation

Processes driving changes in exchangeable sediment N during sediment dewatering and rehydration are not entirely known and need to be investigated more thoroughly. A reduction in exchangeable sediment N in partially dewatered and rehydrated sediments indicated the occurrence of nitrification (Mitchell and Baldwin 1999). Since the pH of water during sediment rehydration was near 7.0 (James et al. 2002), direct volatilization of NH_4-N to NH_3-N (Reddy and Patrick 1975) was probably minor. In contrast, nearly complete dewatering (i.e., 95 percent) followed by rehydration resulted in very high exchangeable sediment N concentrations. Others have found high porewater NH_4-N and exchangeable sediment N after complete dewatering and rehydration of sediments (De Groot and Van Wijck 1993, James et al. 2001). One mechanism believed to be responsible for this response is high bacterial mortality, and release of soluble N during cell lysis (De Groot and Van Wijck 1993, Baldwin and Mitchell 2000). Rehydration of dewatered sediments with initially oxygenated lake water may have also accelerated mineralization of organic N to NH_4-N by newly populated microbial communities, additionally contributing to the high concentrations of exchangeable sediment N.

An important finding of this study was the overall significant reduction in sediment total N concentrations (18 percent reduction over controls) as a result of dewatering sediment by more than 50 percent (i.e., treatments 3 and 4). These results suggested the occurrence of coupled nitrification-denitrification during the dewatering-rehydration process. Downward shifts in the eH of water and the occurrence of anoxia during the rehydration process implicated the possibility of N loss via denitrification (James et al. 2002). However, oxidation of NH_4-N via nitrification is required before denitrification can take place. Zones of oxygen in the interstices of the sediment, surrounded by otherwise anoxic conditions (Baldwin and Mitchell 2000), may have led to nitrification followed by denitrification and loss of N from the sediment cores. Very high rates of both NH_4-N and NO_3+NO_2-N release from sediment dewatered by 95 percent coupled with variations in redox both within the sediment porewater and in the overlying water during rehydration could drive nitrification and denitrification, resulting in a loss of total sediment N from the sediment. Our observations of total sediment N dissipation due to sediment dewatering and rehydration are consistent with the findings of De Groot and Van Wijck (1993) and James et al. (2001) for dewatered marsh and lake sediments, respectively. Others have demonstrated the loss of total N from dewatered and rehydrated soils (Reddy and Patrick 1975, Minzoni et al. 1988).

An interesting observation of this study was that variations in exchangeable sediment N only accounted for about 64 percent of the variation in *P. pectinatus* biomass. In particular, even though exchangeable sediment N concentrations were greatest for sediments that were dewatered by 95 percent and rehydrated, *P. pectinatus* biomass exhibited only modest increases ($p > 0.05$) over biomass levels of plants grown on sediments that were not entirely dewatered and exhibited a two-fold lower exchangeable sediment N concentration. Perhaps the lack of a greater growth response to the elevated exchangeable sediment N concentrations was due to lack of N limitation on growth at these concentration levels. However, macrophyte growth on sediments that were dewatered by 95 percent may have been limited by other factors such as sediment textural characteristics. Sediments experimentally dewatered by 95 percent exhibited substantial consolidation and a very high sediment density, even after rehydration, which could have impeded root development and deep penetration into the sediment, thereby limiting the maximum potential growth that might be achieved on these N-rich sediments.

Results of this study suggest the possibility of manipulating exchangeable sediment N concentrations either negatively or positively via sediment dewatering to affect macrophyte growth and total sediment N concentrations. Pool drawdown over different durations may be used to dewater sediments to various moisture contents to achieve changes in exchangeable and total sediment N. Sediments in shallow aquatic systems may be driven toward temporary N limitation of macrophyte growth through partial sediment dewatering to control or reduce macrophyte growth. In contrast, nearly complete sediment dewatering may be desirable to temporarily enhance exchangeable sediment N availability for macrophyte growth. The latter scenario is applicable for restoration and enhancement of macrophyte growth in shallow aquatic systems that have lost this component. Finally, both partial and complete sediment dewatering followed by rehydration can also lead to overall loss of total sediment N, most likely via coupled nitrification-denitrification processes, which can be beneficial in dissipating sediment N for lakes with excessive sediment N storage (De Groot and Van Wijck 1993). In particular, conducting pool fluctuations to dewater sediments to various states may be a very useful and feasible management tool for both regulating macrophyte communities and stimulating N dissipation in N-enriched systems such as the Mississippi River and its associated backwaters and pools.

ACKNOWLEDGMENTS: This research was funded and conducted for partial fulfillment of the Aquatic Plant Control Research Program Work Unit 33309. We gratefully acknowledge Mses. Laura Blegen, Alyssa Boock, Susan Fox (Analytical Services, Inc.), Emily Gilles, and Stephanie Sweeney, and Messrs. Dale Dressel (Analytical Services, Inc.), Alan Lamphere, and Matthew Pommier of the Eau Galle Aquatic Ecology Laboratory, Spring Valley, WI, for field sampling and chemical analysis. Additional funding for this study was provided by the U.S. Army Engineer District, St. Paul.

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> James, W. F., Eakin, H. L., and Barko, J. W. (2003). "Manipulation of sediment nitrogen via dewatering and rehydration: Implications for macrophyte control and N dissipation," APCRP Technical Notes Collection (ERDC/TN APCRP-EA-06), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *http://www.wes.army.mil/el/aqua.*

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